Kaons Redux: Executive Summary of Fermilab Proposal P996*

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Measurement of the $K^+ \to \pi^+ \nu\bar{\nu}$ Decay at Fermilab

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Abstract

The dramatic physics reach of a precision measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ is due to its sensitivity to most physics models which extend the Standard Model to solve its considerable problems. The extreme suppression in the Standard Model (<1 part in 10 billion) allows new physics to contribute dramatically to the branching fraction with enhancements of up to factors of 5. This sensitivity is unique in quark flavor physics and probes essentially all models of new physics that couple to quarks within the reach of the LHC. Furthermore, a high precision measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ is sensitive to many models of new physics with mass scales well beyond the direct reach of the LHC. The experimental challenge of suppressing backgrounds to enable measurement of $K^+ \to \pi^+ \nu\bar{\nu}$ at the 1 in 10-billion Standard Model rate has been met successfully. Several events of $K^+ \to \pi^+ \nu\bar{\nu}$ decay have been clearly observed at BNL by using a carefully refined technique involving stopped low-energy kaons. Operating the Tevatron after Run-II as a 150 GeV high-duty-factor synchrotron "Stretcher" offers the opportunity to reach more than two orders of magnitude greater sensitivity based on incremental improvements to the experimental techniques firmly established at BNL, yielding precision comparable to the Standard Model prediction which is the most accurate among all loop calculations. The Tevatron Stretcher would be a unique facility that would provide ideal properties for this high-precision measurement, allowing the demonstrated performance of the BNL experiment to be improved considerably and the technique extrapolated with confidence to the new experiment at Fermilab. Opportunities for further advances to attain even higher precision would be made possible by the advent of Project X.

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Executive Summary

Precise measurement of the ultra-rare $K^+ \to \pi^+\nu\bar{\nu}$ decay is one of the most incisive probes of quark flavor physics. Due to its sensitivity to the virtual presence of high mass particles, $K^+ \to \pi^+\nu\bar{\nu}$ also explores physics complementary to the LHC and to other prominant flavor physics studies. The extraordinary precision of the theoretically robust Standard Model calculations for $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0_L \to \pi^0\nu\bar{\nu}$, unique among weak interaction quark processes, results in branching fractions predicted with 5-10% precision at the level below 10^{-10}. The extreme suppression allows new physics to contribute dramatically to the branching fractions with enhancements of up to factors of 5 above the Standard Model level. The Fermilab experiment discussed here (P996) would have $> 5\sigma$ discovery potential for new physics, covering most models accessible at the LHC, and many that go beyond its reach, even for enhancements of the branching fraction as small as 30% above the Standard Model level.

Observing $K^+ \to \pi^+\nu\bar{\nu}$ decay at the 10^{-10} branching ratio level represents a significant experimental challenge. The experimentally weak signal consists of a charged kaon followed by a charged pion, $K^+ \to \pi^+$, with no other observed particles. Potential backgrounds, primarily from other K decays at branching ratios as much as 10 orders of magnitude larger, have similar signatures. Therefore, the experimental strategy involves proving that candidate events have low probabilities of being due to background. To be successful at detecting $K^+ \to \pi^+\nu\bar{\nu}$ and separating it from background, the detector must have powerful π^+ particle identification so that $K^+ \to \mu^+\nu_\mu$ ($K_{\mu 2}$) and $K^+ \to \mu^+\nu_\mu\gamma$ ($K_{\mu 2\gamma}$) decays can be rejected, highly efficient 4π solid-angle photon detection coverage for vetoing $K^+ \to \pi^+\pi^0$ ($K_{\pi 2}$) events and other decays, and an efficient K^+ identification system for eliminating beam-related backgrounds.

Spanning a period of two decades, BNL AGS experiments E787 and E949 [1] refined the technique for measuring $K^+ \to \pi^+\nu\bar{\nu}$ in three experimental generations culminating in discovery of a handful (7) of events. The result was $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = 1.73^{+1.15}_{-1.05} \times 10^{-10}$ and the estimated probability that all the candidates observed by E787 and E949 were due to background was <0.001. The measured branching ratio, although twice as large as the current SM prediction of $\mathcal{B}(K^+ \to \pi^+\nu\bar{\nu}) = (0.85 \pm 0.15) \times 10^{-10}$, is consistent with the prediction within the statistical uncertainty. The experiment NA62 under development at CERN[1] employs a promising but new technique and aims to improve upon the sensitivity of E949 by an order of magnitude. Another related project KOTO at JPARC is entering the first phase of a serious attempt to observe $K^0_L \to \pi^0\nu\bar{\nu}$; it is currently aiming for an initial observation at the SM level.

A unique opportunity now exits at Fermilab to perform the fourth generation $K^+ \to \pi^+\nu\bar{\nu}$ measurement aiming for the ultimate sensitivity 1000 event experiment. Extremely high rates of low-energy charged kaons under ideal conditions for a measurement of the rare process $K^+ \to \pi^+\nu\bar{\nu}$ are available at Fermilab once Run-II of the collider is completed. The "Tevatron Stretcher" scheme involves operating the Tevatron as a 95%-duty-factor 150-GeV synchrotron "stretcher" of the beam supplied by 10% of the available Main Injector flux. With kaon production from the Tevatron Stretcher, the demonstrated performance of the BNL technique can be extrapolated with confidence to a Fermilab experiment capable of reaching <5% precision at the SM level.

The sensitivity of this experiment at Fermilab, can be confidently extrapolated from the experience of E949 by taking advantage of the potential for incremental but subsantial improvements in a well-established technique. Sensitivity and background estimates can be reliably made relative to the measurements for E949.[2] For the new Fermilab experiment, kaon beams of a lower momentum 550 MeV/c will be used, in order to substantially improve the kaon stopping efficiency. Low-energy

[1]The NA62 measurement of $K^+ \to \pi^+\nu\bar{\nu}$ is one of the only major non-LHC projects to be launched at CERN in recent years.

[2]Operation of E949 was stopped after one short run.

K^+ production cross sections at 0° for 150-GeV protons were estimated from target production simulations, resulting in favorable yields compared to BNL. A new design for a shorter, higher acceptance charged K^+ beam has been made, leading to higher flux with good pion suppression. In spite of the order of magnitude higher kaon stopping rate, the instantaneous rates in the Fermilab experiment will be comparable to or lower than those at BNL.

The spectrometer proposed for experiment P996 is illustrated in Fig. 0.1. The basic approach

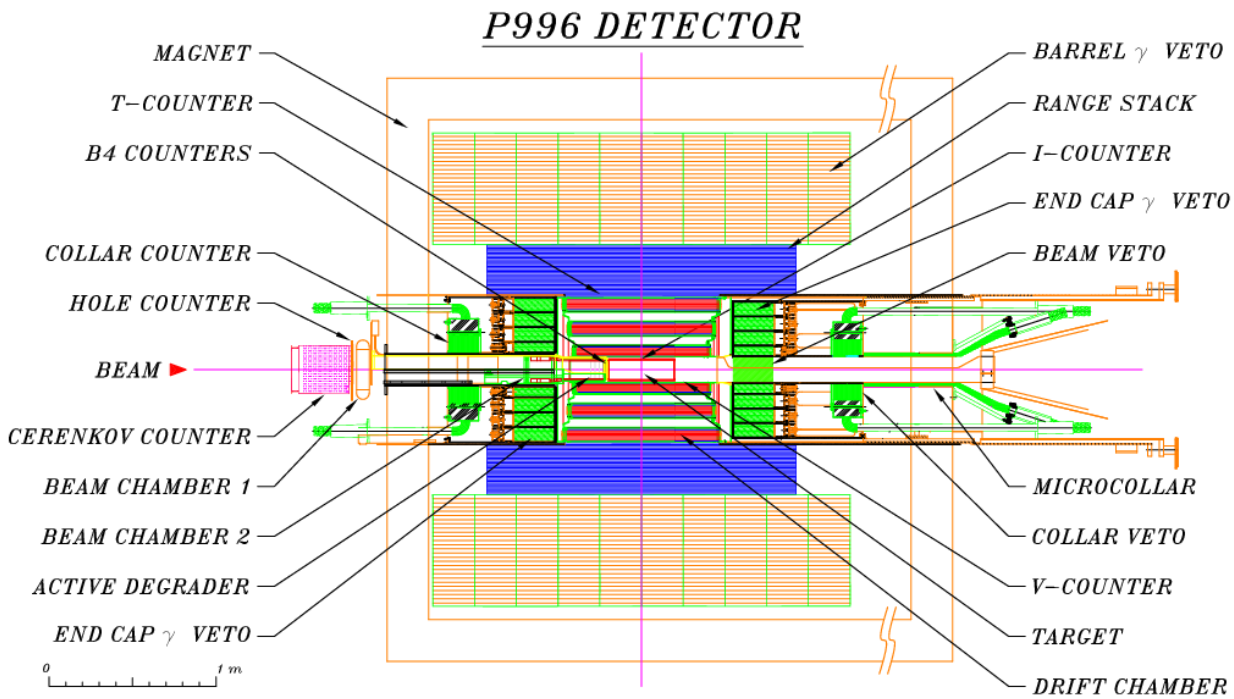

Figure 0.1: Elevation view of the proposed P996 detector. The beam enters from the left, and several key components are labeled.

employed by E949 will be used; kaons will be stopped in a highly segmented active target and $K^+ \to \pi^+\nu\bar{\nu}$ events will be observed using a high precision central drift chamber surrounded by segmented scintillation detectors for measuring pion range, energy and the $\pi - \mu - e$ decay sequence and an efficient 4π solid angle calorimeter for vetoing events accompanied by gamma rays. An acceptance gain of >10 will be attained with reduced backgrounds compared to E949 by making several incremental advancements to the technique. Many of the estimated improvements which result in superior background rejection and higher acceptance have been quantified using E949 data.

In the new $K^+ \to \pi^+\nu\bar{\nu}$ experiment, an existing solenoid magnet, such at the CDF solenoid (likely located in the CDF hall), run with a 1.25-T magnetic field, will be used allowing a longer detector with increased solid angle acceptance and improved momentum resolution. Several other improvements are anticipated including finer segmentation of the pion stopping-region ‘Range Stack’ (RS) detectors. The improved design will substantially reduce muon backgrounds, providing a significant gain in acceptance due to the application of less stringent cuts. Finer segmentation of the RS will also facilitate improvements in π^+ tracking prior to stopping. Improved momentum resolution will result in improved two-body background rejection and result in acceptance gains. In addition, the photon veto detector will also be enhanced by using more radiation lengths than in E949, and by reducing inactive materials.

The numbers of events expected for the new Fermilab experiment with the Main Injector/Tevatron Stretcher combination would be about 200/year - two orders of magnitude greater than achieved at BNL. In a 3-5 year period, a precision of <5%, including projected background subtraction, would be anticipated if the branching ratio is consistent with the SM. Further improvements in experimental precision would be anticipated with the higher kaon fluxes available at Project X.

The cost estimate for P996 construction based on a five year project is shown in table (Table 0.1) including 60% contingency on all items. Figure 0.2 shows a projected time distribution of construction costs. Estimates were made for Tevatron modifications, extraction systems and lines, the target and beam dump, the kaon beamline, and the detector. For the kaon beamline, estimates were based on the cost of the LESB-III (Low Energy Separated Beam) [2] beamline for the BNL E787 and E949 experiments. Reuse of existing Fermilab slow-extraction equipment would reduce capital beamline costs as would use of the quadrupole magnets and associated spare equipment of the LESB-III beamline at BNL. Operation of the Tevatron as a stretcher is estimated to cost approximately $9M/yr above the costs for maintaining the Tevatron in a cold state.

This proposal involves a modest-scale experiment requiring no civil construction that will exploit unique accelerator facilities at Fermilab and a well-developed experimental technique to make a precision measurement of the branching fraction of the decay $K^+ \to \pi^+\nu\bar{\nu}$. Consequently, construction can be completed in about 2.5 years; moving quickly would put the experiment on a very competitive timeline with the NA62 experiment at CERN and KOTO at JPARC since P996 uniquely builds on the established technique of the BNL experiments. The international Fermilab P996 collaboration includes a solid base of leadership and veterans of BNL E787 and E949 which observed $K^+ \to \pi^+\nu\bar{\nu}$, as well as leadership and veterans of other successful rare K-decay experiments at BNL and Fermilab. This collaboration would establish a strong foundation on which to realize the rich kaon physics potential of Project X.

References

[1] A. V. Artamonov *et al.*, Phys. Rev. D **79**, 092004 (2009).

[2] J. Doornbos *et al.*, Nucl.Instrum.Meth.**A444** 546 (2000).

Table 0.1: Estimated project cost. All costs in FY10 $k.

WBS element		Description	Total Cost	60% conting.	Total w/cont.
1.0		**TPC**	**$33M**	**$20M**	**$53M**
1.1		**Accelerator and Beams**	**7,500**	**4,500**	**12,000**
	1.1.1	Tevatron Modifications	940	560	1,500
	1.1.2	Extraction and Lines	1,250	750	2,000
	1.1.3	Target and Dump	940	560	1,500
	1.1.4	Kaon Beam	4,370	2630	7,000
1.2		**Detector**	**22,390**	**13,430**	**35,820**
	1.2.1	Spectrometer Magnet	500	300	800
	1.2.2	Beam and Target	600	360	960
	1.2.3	Drift Chamber	1,900	1,140	3,040
	1.2.4	Range Stack	2,500	1,500	4,000
	1.2.5	Photon Veto	3,000	1,800	4,800
	1.2.6	Electronics	4,000	2,400	6,400
	1.2.7	Trigger and DAQ	2,000	1,200	3,200
	1.2.8	Software and Computing	2,000	1,200	3,200
	1.2.9	Installation and Integration	5,890	3,530	9,420
1.3		**Project Management**	**2,740**	**1,640**	**4,380**
1.4		**OPC**	**700**	**420**	**1,120**
	1.4.1	R&D	300	180	480
	1.4.2	Comissioning	400	240	640

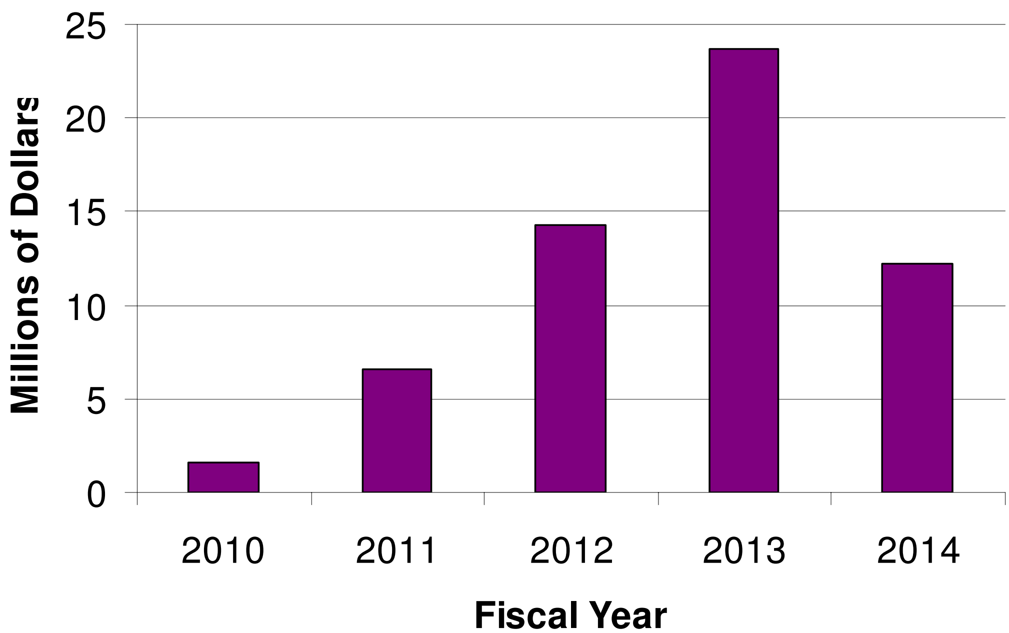

Figure 0.2: A funding profile that assumes an estimated TPC of $58M in then-year dollars. While based on general considerations rather than detailed plans, a funding profile close to this will be necessary to meet the proposed schedule.